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PHYSICAL PROCESSES RELATED TO

SEA-ICE DIVERGENCE



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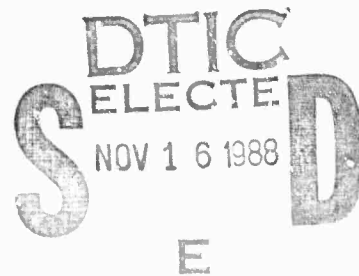
PHYSICAL PROCESSES RELATED TO  
SEA-ICE DIVERGENCE



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A Report to the Naval Ocean Research and Development Activity  
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<p>This report documents the results of a study of a number of sea ice processes in the Arctic Basin. Seasonal sea ice kinematics were closely scrutinized, and their space and time scales calculated. In addition, factors concerning sea ice thermodynamics were considered. Finally, direct comparisons were made between observed ice velocities and corresponding ice velocities from the Polar Ice Prediction System (PIPS). One of the primary objectives of this work was to provide a wide range of information with which one could validate the mechanics and predictions of the PIPS. Factors that were studied include the grid size and time step of the PIPS, the scale of important forcing variables, the formulation of heat fluxes within the model ice field, and steps to be considered in the attempt to produce the most realistic predictions possible.</p> <p>depends. No final prediction/models. etc.)</p>			
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## ABSTRACT

Seasonal time histories of ice motion parameters had been calculated by Lewis et al. (1988a) for various regions in the arctic. The motion of the sea ice was considered in terms of divergence, vorticity, deformation rate, and ice translation speed. The calculations indicated that the divergence was the most temporally and spatially variable of the ice kinematic parameters for all seasons. It was found that significant variations in divergence occurred in some areas on the order of 100 km and with an e-folding time of ~2 hours. In contrast, significant variations in the translation speed occurred in some areas on the order of 700 km and with a time scale of over 80 hours.

In this report, the small space and time scales of pack ice divergence are investigated. The small time scale of the ice pack divergence is a reflection of gravitational and buoyancy forces. These do not allow for any long term (4-5 days) variations in the divergence, a characteristic not reflected by other ice kinematic parameters. The small space scale of the ice pack divergence is shown to be a direct result of its short time scale. These results imply a need for horizontal pressure gradient terms in the model equations of the Polar Ice Prediction System (PIPS) to account for gravitational and buoyancy forces. Without such terms, the PIPS will likely produce unreliable estimates for ice pack divergence. This is both for the frequency of oscillation and the spatial extent of regions of divergence or convergence.

## 1. INTRODUCTION

Over the past decade, our knowledge of sea-ice processes and ice kinematics in the arctic has been enhanced considerably. Pioneer investigations into the mechanics of sea-ice motion in the arctic were conducted by Hibler (1974), McPhee (1978), and Colony and Thorndike (1980). Most recently, Lewis et al. (1988a) completed an investigation of a number of sea-ice processes in the Arctic Basin. In that study seasonal time histories of ice divergence ( $D$ ), vorticity ( $\zeta$ ), deformation rate ( $T$ ), and translation speed ( $U$ ) were calculated using time histories of position data from drifting buoys in the arctic during May, August, and November, 1979. These basic modes of motion with respect to ice are referred to as ice kinematic parameters (IKP). The results were used to determine seasonal space and time scales of  $D$ ,  $\zeta$ ,  $T$ , and  $U$  in the arctic. An e-folding scale was used as a measure of the temporal coherency. Spatial variability was defined in terms of the degree of similarity between the magnitudes of a parameter at various locations.

It was found that ice-pack divergence had the largest temporal and spatial variability of the IKP during all seasons studied. Spatial variations in divergence ranged from only 100 to 200 km. The time scales were as low as  $\sim 2$  hours. In contrast, significant variations in the translation speed occurred in some areas on the order of 700 km and over a time period as great as 80 hours. Overall, the short space and time scales of ice-pack divergence were not reflected in the other ice kinematic parameters.

Divergence of the ice pack deals with the opening and closing of leads and the production of ice ridges. As such, divergence is related to under-ice noise, the production of thick, multi-year ice floes, and polar atmospheric heat fluxes. Thus, divergence is not only related to important physical phenomena, but it is also of great operational importance to military activities in the arctic. Clearly, the physical processes governing the small spatial and temporal variability of ice-pack divergence are important and need to be understood.

In addition to data supplied by the remote-sensing of drifting buoys in the arctic, an alternative method used to monitor various sea-ice processes in the arctic is numerical modeling. Hibler (1979) and Hibler and Tucker (1979) developed a dynamic/thermodynamic sea-ice model which produces results in good agreement with general ice conditions. The model, now referred

to as the Polar Ice Prediction System (PIPS), has been upgraded and implemented on Navy computers (Preller, 1985).

As part of an effort to verify PIPS, Lewis et al. (1988a,b) conducted a detailed study of sea-ice processes, including kinematics (as described above), thermal processes, and direct model/observation comparisons. Their efforts provided information on sea-ice processes and their space and time scales based on observed data for use in determining if PIPS is handling such processes in the most correct manner. Lewis et al. (1988b) provide a synopsis of observed results, comparisons between observed and model results, and recommendations for adjustments to PIPS.

The present study was undertaken as a follow-up to Lewis et al. (1988a,b) and focuses upon the determination of the physical and mechanical processes underlying sea-ice divergence. Because divergence is of such operational importance to military efforts in the arctic, an accurate assessment of divergence by PIPS is critical. The space and time scales of divergence relate directly to the time step and grid size of the PIPS. The mechanisms responsible for these scales are related to the force balance equations incorporated in the PIPS. Therefore, knowledge of the physical forces underlying divergence will not only enhance our understanding of the processes and mechanics governing ice motion but also aid in verifying and implementing the proper force balances in the PIPS model.

## 2. TIME SCALES

The calculations of Lewis et al. (1988a) show that ice-pack divergence is the most temporally incoherent of the IKP. The great majority of the divergence time scales were of the order of 2-3 hours while other IKP had time scales several times longer (Table 1). Initially, one might suspect

	Spring	Summer	Fall
D	2.3-26.8	2.6-15.2	1.7-10.1
$\zeta$	8.0-38.5	9.2-80.0	20.0-46.1
T	10.2-32.8	4.9-15.9	2.7-24.3
U	14.9-80.0	13.0-31.5	21.3-27.4

Table 1. Range of e-folding times (hours) for each ice kinematic parameter during spring, summer, and fall, 1979. An e-folding time of 80 hours implies that the temporal autocorrelation never fell below  $e^{-1}$  (from Lewis et al., 1988a).

that the short-term variability of the divergence is a result of measurement noise. However, Lewis et al. (1988b) found this to be an unlikely possibility. Another factor could be the internal stresses of sea ice. The effect of internal stresses would be seen primarily by ice divergence since it is directly linked to the tensile and compressive strength of ice. Therefore, internal stress is one mechanism which would predominantly affect ice divergence and not other modes of kinematic motion.

To fully understand the differences in the time scales of the IKP, we must first consider the implication of the e-folding time scales. The e-folding time is that phase lag at which the correlation of a signal with itself falls to  $e^{-1} = 0.36$ . If we are dealing with a purely sinusoidal signal, the correlation drops to  $e^{-1}$  when the sinusoid is shifted  $79.4^\circ$  with respect to itself. If the period

of oscillation of the sinusoid is T hours, then a  $79.4^\circ$  phase shift translates to a  $T \times 79.4/360$  hour phase shift (approximately 22% of the period).

Therefore, the 2 to 3 hour time scales of pack-ice divergence implies an average period of oscillation of 9 to 13 hours. And the 20 to 25 hour time scales of the other IKP indicate oscillations on the order of 4 to 5 days. Thus, our investigation into the time scales of ice-pack divergence is essentially a determination of why pack ice can undergo significant long-term oscillations (4-5 days) in deformation, rotation, and translation, but not in divergence. These implications of the time scales of kinematic motion are seen in the spectral density of divergence, vorticity, and deformation for 3 regions in the arctic. Fig. 1 shows the average locations of these regions. The spectral estimates of divergence, vorticity, and

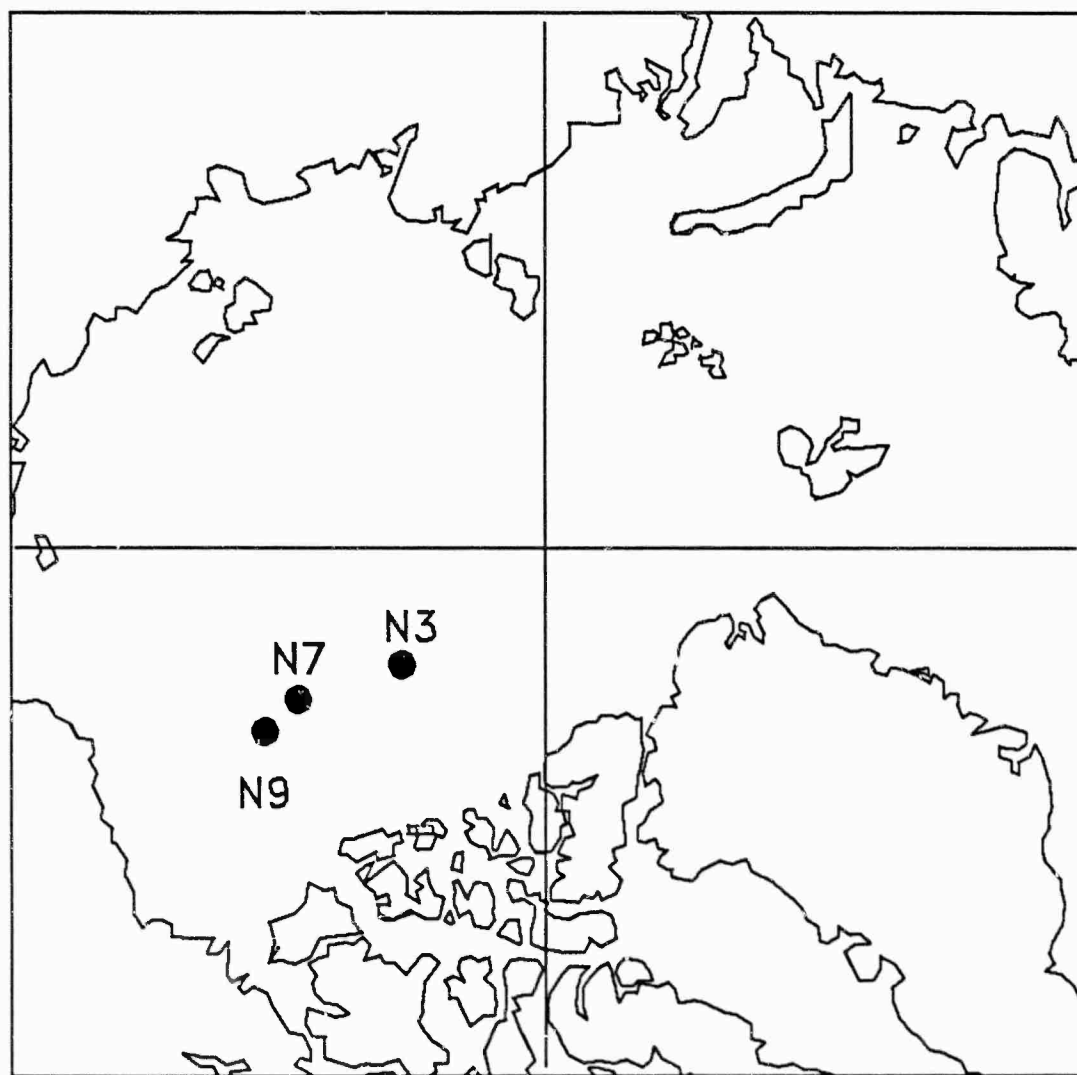


Fig. 1. Average locations during November 1979 of the centroids of the three ice regions considered in the spectral analyses. Each region, as defined in the work of Lewis et al. (1988a), consists of a cluster of 4 or 5 buoys comprising an area of  $\sim 180 \times 10^3 \text{ km}^2$ .

deformation are given in Fig. 2.

In divergent motion, one sees little energy at low frequencies (Figs. 2). Conversely, relatively large energy levels are seen at low frequencies in ice deformation and vorticity. The most simple explanation for such differences is the mass-conserving requirement that horizontal convergence/divergence be compensated by motion in the vertical. In the case of ice, long-period oscillations in rotation rate (vorticity) and shape changes (deformation) can be easily triggered by the passage of atmospheric fronts. But for ice to have long-period divergence/convergence, there must be compensating long-period oscillations in ridge building and keel formation.

Ridge building and keel formation are processes that include the overcoming of 1) the compressive strength of the pack ice, 2) the retarding force of gravity, and 3) the buoyancy forces of the denser sea water. A convergent ice field may fracture the ice, but additional energy is required to push the fractured floes upward against gravity or downward into the ocean. As a ridge or keel grows larger, the restoring forces of buoyancy and gravity become greater. Thus, long-term oscillations in ice-pack divergence would imply long-term upward and downward motion and, essentially, mountainous ice structures. Of course, buoyancy/gravity restoring forces can be overcome to only a limited extent. Therefore, restrictions placed on the amount of vertical movement by the buoyancy/gravity restoring forces can result in smaller time scale oscillations for divergence and a lack of energy at low frequencies. Conversely, rotating and deformative motion are not inhibited by any vertical restoring forces and, therefore, may persist over longer periods of time.

In numerical simulations of divergent ice motion, it is imperative to provide a limit to the amount of vertical motion (i.e., the thickness of the ice) produced by ice convergence. This is done by including the effects of buoyancy/gravity forces in the governing equations. If the model is not equipped with these restorative terms in its force balance equations, it is possible to have higher energy, long-term oscillations for ice-pack divergence. In addition, the model could incorrectly produce thicker ice estimates. The effects of gravity and buoyancy are incorporated through horizontal pressure gradient terms and the hydrostatic buoyancy equation. In the case of negligible vertical accelerations, the hydrostatic equation implies a balance between buoyancy and the vertical pressure gradient:

$$\partial P' / \partial z = -b$$

where  $P'$  is a pressure anomaly due to density variations,  $z$  is depth (positive upwards from the ice surface), and  $b$  is the buoyancy acceleration,

$$b = \rho' g$$

where  $g$  is the acceleration of gravity,  $\rho'$  is the density anomaly of the ice,  $\rho' = \rho_{ice} - \rho_o$ , and  $\rho_o$  is a reference density (that of the ocean in this case). Thus, if the ice and the ocean had the same density,  $\rho'$  would be zero, and there would be no buoyancy acceleration. Since ocean water is denser than ice,  $\rho'$  and  $b$  are negative.

In the horizontal equations of motion, there are typically pressure gradient terms of the form

$$\frac{1}{\rho_o} \frac{\partial P}{\partial x} \qquad \frac{1}{\rho_o} \frac{\partial P}{\partial y}$$

From the above hydrostatic equation, the pressure anomaly at depth  $z$  in the ice is

$$P'(z) = z b.$$

The pressure anomaly averaged over the entire ice thickness  $H$  is just  $-b H/2$ . Thus, the average horizontal pressure gradients are  $-0.5 b \partial H / \partial x$  and  $-0.5 b \partial H / \partial y$ . These last two terms reflect the influence of buoyancy and gravity for the governing equations of an ice model.

As it is now formulated, the PIPS does not include any buoyancy terms. As such, the PIPS predictions of ice pack divergence will likely have relatively large energy, low frequency oscillations. These predictions could be quite misleading if used operationally. Fortunately, correcting this problem is not a major task.

### 3. SPACE SCALES

The space scales of the IKP in the arctic are shown in Table 2. The results indicate that divergence is the most spatially incoherent of the IKP, with space scales as low as 110 km in some regions of the arctic. This minimum length scale of divergence is of the order of the distance between the ice parcels considered. Therefore, the actual minimum length scale may even be somewhat less.

The data suggest that the space scale for divergence may be less than 100 km. It is seen that other IKP have length scales 3-7 times as large as



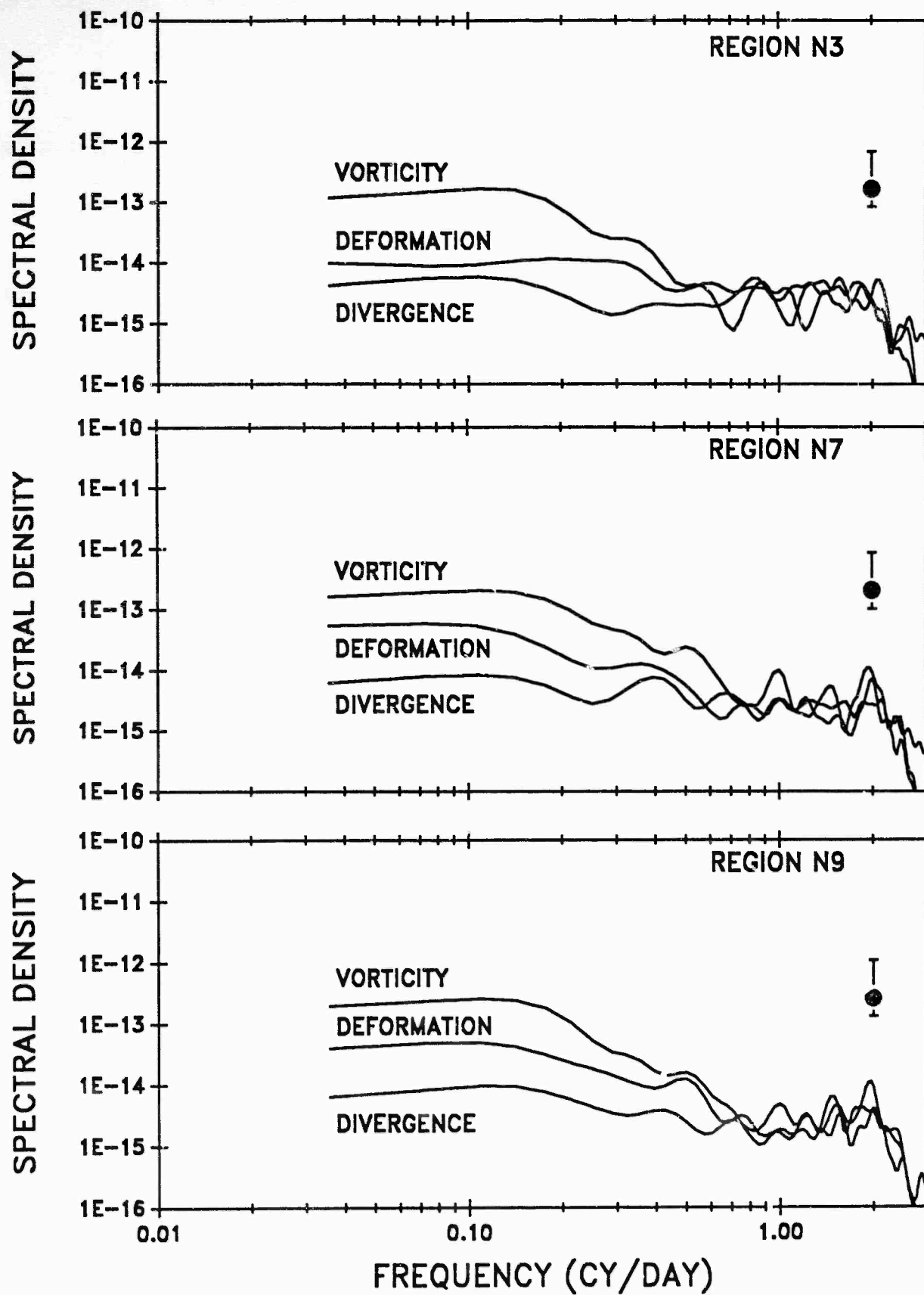


Fig. 2. Power spectra for ice divergence, vorticity, and deformation rate in regions N3 (top), N7 (middle), and N9 (bottom) of the arctic. Confidence intervals of 95% are indicated.

those associated with divergence. In our search to provide the most simple explanation for these space scale differences, we found that the short time scales of ice-pack divergence could directly cause large spatial incoherency. Consider an atmospheric disturbance,  $W(t)$ , which takes time  $T$  to travel length  $L$  across the ice pack. We assume that the moving troughs of such disturbances trigger various modes of responses in the ice pack. We will consider responses B and C. These responses could be ice motions such as divergence and vorticity. Responses B and C are assumed to be oscillatory and have their own time scales,  $T_b$  and  $T_c$ , respectively. Let the position of the trough of the atmospheric disturbance at time  $t$  be given by

$$X(t) = t L/T, 0 \leq t \leq T.$$

Therefore, the initiation of B and C at a point  $x$  begins at time  $t = T x/L$ . Thus, for any  $x$  and  $t$ , responses B and C can be written as:

$$B(x,t) = A_b \sin [(t - T x/L) 2\pi / T_b]$$

$$C(x,t) = A_c \sin [(t - T x/L) 2\pi / T_c],$$

where  $A$  is the amplitude of the oscillation. The above expressions imply that the ice-pack responses are triggered as the trough of the disturbance passes, and they then continue to oscillate at their own natural frequency.

For convenience, we choose as a frame of reference  $X_0$  such that  $t - T X_0/L = 0$  (i.e., B and C are zero). Now consider the space scales  $L_b$  and  $L_c$  which are distances over which B and C, respectively, are continuously positive at time  $t$ :

$$\begin{aligned} \text{Response B - positive from } X_0 = t L/T \text{ to} \\ x_b = (t - T_b/2)L/T \end{aligned}$$

$$\begin{aligned} \text{Response C - positive from } X_0 = t L/T \text{ to} \\ x_c = (t - T_c/2)L/T. \end{aligned}$$

Therefore, length scales of the responses B and C are defined as:

$$L_b = x_b - X_0 = -T_b L/2 T$$

$$L_c = x_c - X_0 = -T_c L/2 T.$$

Hence, it is shown that there is a simple one-to-one relation between the relative magnitudes of space and time scales. It follows that modes of motion which operate on small time scales (e.g., ice pack divergence) will also exhibit a high

	Spring	Summer	Fall
D	195	110	160
$\zeta$	345	280	295
T	640	520	415
U	660	705	665

Table 2. Length scales (km) for ice kinematic parameters for spring, summer, and fall, 1979 (from Lewis et al., 1988a).

degree of spatial variability. And motions that are coherent in time will tend to be spatially consistent. This concept is particularly relevant to numerical simulations. If the forces producing temporal variability are properly handled in a numerical model, then the space scales of the model predictions should be correct. Thus, for the PIPS, the primary concern is to better model the time scales of the IKP.

#### 4. CONCLUSIONS

In general, ice divergence in the arctic is the most spatially and temporally variable of the basic modes of motion. Significant variations in divergent motion can occur on the order of 110 km and within ~2 hours. Divergence of the ice pack deals with the opening and closing of leads, the production of ice ridges and thicker ice, under-ice noise, and polar atmospheric heat fluxes. In addition, divergence is also operationally significant to military activities in the arctic. Because ice divergence is associated with minimum space and time scales in the arctic, it is one of the primary modes of motion on which the time step of the PIPS model should be based. The extent to which we understand the processes underlying divergent motion and incorporate this knowledge into the force balance equations used in the PIPS is particularly critical if decisions concerning military strategy and tactics are to be based upon PIPS forecasts.

The short time scales of ice-pack divergence can be explained physically by considering the buoyancy/gravity restoring forces at work in ice. These forces act to limit the size of the ice ridges and keels created in ice convergence and, consequently, to restrict the amount of energy in this mode of motion. Ice-pack divergence is, thus, a mode of motion characterized by smaller time scale oscillations with very little energy at lower frequencies. In contrast, the other kinematic motions

are not restrained by such restoring forces, possess larger energy levels at lower frequencies and, as such, can sustain long-term variations.

It is shown analytically that there can be a simple one-to-one relationship between temporal and spatial variability for a given mode of motion. Therefore, the mechanisms at work to produce the short time scales of ice-pack divergence can also be responsible for its small space scales.

Our results indicate that the Polar Ice Prediction System will likely produce unreliable estimates for ice-pack divergence. This is both for the frequency of oscillation and the spatial extent of regions of divergence or convergence. The problem lies in the fact that the PIPS does not incorporate horizontal pressure gradient terms into its model equations. Fortunately, this is an easily rectified situation.

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